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13. ABSTRACT *(Maximum 200 words)*

This report describes the progress to date of a Phase II Small Business Innovation Research (SBIR) program being performed for Electronics Systems Center (ESC) under Contract No. F19628-95-C-0233. The overall objective of the Phase II research is to improve and enhance MUSSLE (Multiple Sensor Statistical Likelihood Estimator), the Multi-Sensor Integration algorithm under development for the E-3 AWACS platform. Modifications to the software completed to date include: enhanced three dimensional report processing for the Contact-to-Track Association module, MATCH; restructuring of the MUSSLE database so that ambiguous correlations are maintained in a cluster; improvements to the throughput speed of the algorithm; improvements to the passive tracking module; and improvements to the responses to operator switch actions. In addition to the code modifications, we produced a throughput and memory requirements analysis of the MUSSLE program.

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AWACS MULTI-SENSOR INTEGRATION AND FUSION ID

Phase II Interim Report

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November 15, 1996

Contract Number F19628-95-C-0233

Prepared for

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Hanscom AFB, MA 01731-1806

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Acknowledgments

The high quality of the research performed and software developed during the first year of this contract could not have been achieved without the assistance of a number of individuals. First, I would like to thank the personnel at MITRE for their dedicated support and conscientious evaluation of the prototype versions of the software. An incomplete list of the many fine people at MITRE includes, Mr. Pete Smyton, Mr. Dave Proctor, Ms. Isabel Meyer, Mr. Dave Crawford and Mr. Chris Berube. Here at the Hampton Office of Daniel H. Wagner Associates, Dr. Robert H. Overton provided his expertise on a variety of tracking and correlation issues. Dr. Eric C. Butts, of the Pennsylvania office, provided all of the design and programming modifications for the Contact-to-Track association module, MATCH. Dr. David P. Kierstead and Mr. John A. Crowe, of the Washington office, demonstrated the DFCA for the Minuteman III Follow-On Test and Evaluation program. Finally, I wish to acknowledge Mr. Richard S. Thompson, without whose considerable programming skills the MSI algorithm would be only a theoretical entity.

1. Introduction

1.1. Background

The AWACS Commander is responsible for managing air tracks and combat in the airspace of the E-3's radar umbrella. To meet this requirement he must have systems at his disposal that can fuse track position and identification (ID) data obtained from a variety of sources, including organic E-3 sensors and offboard reports. This data fusion process must be complete, accurate, and above all, reliable. Even one miscorrelation or misidentification of a track can be critical. Worse yet, in today's complex high track-density Joint and Allied operational environment, a few misidentifications or miscorrelations by an overly simplistic data fusion system can quickly propagate to more and more errors, until the track picture becomes chaotic.

Daniel H. Wagner Associates, Inc., under a previous SBIR program, developed a multi-sensor integration (MSI) algorithm that solves the problem of combining information from on-board sensors into a single tactical picture. That software was subjected to a ground breaking test and evaluation process in ESC's Fusion Evaluation Testbed. In a test and evaluation debrief given on December 14, 1993, the results showed the Wagner MSI algorithm (hereinafter referred to as MUSSLE — Multiple Sensor Statistical Likelihood Estimator) to be very effective in automatically developing tracks from multiple sensors and to outperform the current AWACS tracker in maintaining track, especially on maneuvering targets.

In November of 1995, Wagner Associates was awarded a Phase II Small Business Innovation Research contract to enhance and improve the performance of MUSSLE. The enhancements are intended to produce prototype MSI software which will handle the off board data sources, the new Electronic Support Measures (ESM) and the remaining on board sensors at a level of performance that exceeds that of the current AWACS tracker.

1.2. Scope

This interim report documents and details the specific progress made to date on the tasks specified in the Phase II SBIR program being performed for Electronics Systems Center (ESC) under Contract No. F19628-95-C-0233. This covers the work performed by Wagner Associates during the period November 7, 1995 to November 7, 1996. The document begins with a list of the tasks as specified in the statement of work. The progress to date on each task is summarized. Specific accomplishments and modifications to the code are then detailed in a chronological fashion.

2. Phase II Tasks and Summaries

Below is the list of tasks as specified in the Statement of Work. The numbering of the tasks corresponds to the numbering from the contractual document and thus does not correspond to the paragraph numbering of this document. Below each task description is a brief summary of the current status of the task. As the reader will note, the tasks have not been performed in numerical order.

Task 4.1.1. Develop Registration Algorithm. *In this task, the contractor shall enhance the existing data registration algorithm to include features that solve specific gridlock problems. The contractor shall develop a methodology to improve discrimination between targets at or near the same azimuth. The contractor shall add algorithms to estimate time biases or consistent reporting delays. The contractor shall add routines that more carefully select registration pairs (i.e., pairs of tracks, each from a different sensor). The contractor shall compile and test the software on in-house computers using test cases generated in house and unclassified extracts from the Air Force testbed data. The product will be an algorithm in Ada, adjunct to MUSSLE.*

No work has been done on this task. This task will be performed in the second year of the contract.

Task 4.1.2. Implement Pseudo-Measurement Tracking Of Remote Data. *In this task, the contractor shall develop methodologies for pre-processing remote data to remove errors introduced by the remote unit's filter. The contractor shall develop tables of parameter estimates for various types of filters used on remote tracks (e.g., alpha-beta trackers and Kalman-Bucy filters). The contractor shall implement pre-processing routines to extract proxy reports in place of original (non-filtered) sensor reports. The contractor shall develop consistent techniques to adjust the covariances of these pseudo-measurements in order to achieve maximum performance in the MUSSLE tracking and correlation algorithms. The contractor shall link this new code into the input process architecture of the existing MUSSLE code. The contractor shall compile and test the software on in-house computers using test cases generated in house and unclassified extracts from the Air Force testbed data. The product will be a package, in Ada, that handles the inaccuracy problems caused by poor tracker performance at remote sources.*

No work has been done on this task. This task will be performed in the second year of the contract.

Task 4.1.3. Add Track Quality Reporting. *In this task, the contractor shall develop algorithms and software that provide a "track quality" output along with normal track output from the MUSSLE MSI. The contractor shall apply the algorithms to the final output stage of MUSSLE, only to tracks reported out to the rest of the system. The contractor shall compile and test the software on in-house computers using test cases generated in house and unclassified extracts from the Air Force testbed data. The contractor shall demonstrate how the improved track quality measure will increase the accuracy of the track information on the link. The product will be a track quality module, in Ada, integrated into the rest of MUSSLE.*

No work has been done on this task. This task will be performed in the second year of the contract.

Task 4.1.4. Add Stochastic ID Fusion. *In this task, the contractor shall develop algorithms and data structure to compute and save alternative IDs for system tracks. These alternative IDs will carry probability measures and these measures will be updated with each new report. The contractor shall compile and test the software on in-house computers using test cases generated in house and unclassified extracts from the Air Force testbed data. The product will be an improved correlation algorithm, added data structures in the basic algorithm, and a new module, in Ada, to compute ID confidence for all reported tracks.*

No work has been done on this task. This task will be performed in the second year of the contract.

Task 4.1.5. Respond To User Inputs. *In this task, the contractor shall make various modifications to the MUSSLE algorithm to improve the quality, utility, and believability of the algorithm output. The contractor shall interview operators and experienced AWACS watch officers. The contractor shall review material prepared by the Air Force and the MITRE Corporation resulting from user demonstrations. The contractor shall prepare a list of potential modifications with options for total cost and schedule impact. The contractor shall work with the Air force and the MITRE representatives to prioritize this list and develop a plan that fits within the budget of this task. The contractor shall then implement the planned improvements. The contractor shall compile and test the enhancements on in-house computers using test cases generated in house and unclassified extracts from the Air Force testbed data. The product will be a final, improved version of the MUSSLE software, fully tested and ready for integration in the FET and implementation on prototype hardware.*

Recent work has been done to improve the consistency of responding to the operator switch actions INITIATE and REINITIATE. A list of desired improvements has been generated by

MITRE personnel based on responses from experienced AWACS operators. The final decision as to which items in the list should be implemented has not yet been made. The remaining part of this task will be performed in the second year of this contract.

Task 4.1.6. Integrate Improved Algorithms in the FET. *In this task, the contractor shall visit the Hanscom AFB and integrate the software revisions in the FET. The contractor shall perform this task in two stages. In stage one, the contractor shall make an initial visit to load, compile, and test the software in the FET and run a series of large- and small-scale tests. The contractor shall make minor corrections to the software on-site to adapt to errors detected or to unexpected changes in the FET interface, in order to ensure that a workable code is available for the Air Force to demonstrate. The contractor shall also develop a complete list of final enhancements and corrections to be made in his own facility. In stage two, the contractor shall make those more involved corrections in our own facility, test them thoroughly, and then make a second visit to Hanscom AFB to install the final version in the FET. The products will be a final, working MSI algorithm, in Ada, working in full demonstration mode at the Hanscom FET and a final report detailing the features and functions of the delivered algorithm.*

The initial delivery of the software was made as specified above. The interim delivery will be made the week of November 18th and will coincide with the delivery of this interim report.

Task 4.1.7. Evaluate Use Of A Single, Contact-To-Track Algorithm. *In this task, the contractor shall implement the MATCH contact-to-track algorithm, in place of the present hierarchical architecture, within the overall MUSSLE envelope. The contractor shall then perform side-by-side tests of the revised architecture and the original MUSSLE code as delivered in Task 6. The contractor shall record results against selected scenarios as detailed in the FET plan, with measures of performance (MOPs) provided by the government. The contractor shall also compare computer time requirements by running identical scenarios side by side. The contractor shall deliver the alternative-architecture version to Hanscom and compile, link, and test it in the FET. The contractor shall assist Air Force and MITRE personnel in demonstrating and performing tests on this version. The product will be a memorandum report comparing the performances of the two alternative architectures and a revised code version installed in the FET.*

We have performed a preliminary investigation into using MATCH to perform the entire MSI function. Depending on the desires of our sponsor, we will either pursue this further or not.

Task 4.1.8. Analyze Timing And Performance. *In this task, the contractor shall develop processing time measures for the MUSSLE and MATCH algorithms. The contractor shall modify the existing target report generation program to provide reports representative of the expected AWACS load considering future sensor suite and offboard reporting. The contractor shall take samples of actual processing times against representative target populations and attempt to determine a function that predicts workload requirements. The contractor shall test this prediction function against appropriate scenarios. The contractor shall work with government representatives to determine the likely maximum report volumes from all the installed sensors and reporting sources in the largest scenario expected or possible. The contractor shall then calculate the total number of computer cycles per second required for the MUSSLE and MATCH algorithms to keep up with the data. The Air Force will provide its best estimate of computer architectures that will be compatible with plans for near- and far-term E-3 upgrades. The contractor shall examine the issues of implementation on multiple computers and compare options of SIMD and MIMD architectures. The contractor shall then lay out a set of compatible computers and interconnections that will handle this largest expected workload. The product will be a memorandum report on algorithm timing results and a proposed hardware architecture design.*

We have completed this task and the memorandum report (CDRL item A001) was delivered to Capt. Caccuitto on October 22, 1996.

Task 4.1.9. Demonstrate MSI Algorithm On Open-Architecture, Parallel Processors. *In this task, the contractor shall acquire hardware compatible with the Air Force's plans for E-3 computer upgrades (including such issues as MIMD versus SIMD, processor manufacturer, operating system, and Ethernet, MIL-STD 1553B, or asynchronous communication modes). The contractor shall install the hardware in its facility in a configuration suitable for testing MSI in-house. The contractor shall then port the Ada code to the processors in accordance with the design in Task 8 and test the system. The contractor shall assign one processor to generate reports from stored scenarios and a second to capture output from the MSI and compare to the ground truth scenario. The product will be a demonstration of the MSI running in the hardware environment and a final report on the installation and its results. The contractor shall continue to use the hardware for marketing and demonstrations in Task 10 and potentially in Phase III activities.*

No work has been done on this task. This task will be performed in the second year of the contract.

Task 4.1.10. Demonstrate Commercial Market Interest. *In this task, the contractor shall approach various prime contractors with the idea of providing MSI systems on open architectures and insertable modules into airborne, shipboard, or ground tracking systems. The contractor shall also research the applicability of MUSSLE to a number of other environments as appropriate. The contractor shall develop scenarios in each candidate civilian application and run the system and record the results. The contractor shall then prepare briefing materials and algorithm descriptions suitable to presentation to Air Force, prime contractor, and civilian organizations. The product will be a complete set of information literature and algorithm description of MUSSLE and a memorandum report of success in applying the algorithm to candidate commercial scenarios.*

The only work performed on this task involves the work performed in the sub-task 4.1.10.1. Additional marketing will be performed in the second year of the contract.

Task 4.1.10.1 Demonstrate Data Fusion/Correlation Algorithm. *As a subtask, install and demonstrate the Data Fusion/Correlation Algorithm (DFCA) in support of the 1996 multi-sensor data fusion algorithm check-out at the National Test Facility (NTF) in Colorado Springs, CO. Perform post-demonstration data analysis. The product will be a demonstration of the DFCA running in the NTF environment and a memorandum report on the installation and its results.*

The installation of the DFCA in the NTF was precluded by the freezing of the test configuration prior to an opportunity for Wagner personnel to install the algorithm. However, the post-demonstration data analysis was completed satisfactorily for the June test. There are additional data sets which the Air Force would like processed and this may be performed in the second year of the contract, depending on available funding.

3. Phase II Detailed Progress and Software Modifications

3.1. Enhancements to MATCH

A major component of the MSI algorithm is the contact-to-track association module MATCH. This module is used to preprocess sensor data which does not come with an assigned local track number. Since all of the data from the radar sensor is of this mature it must be preprocessed by MATCH before processing at the track-to-track correlation level. In this section, we describe the major enhancements made to the MATCH module.

The previous version of MATCH performed two-dimensional tracking only. Thus, the first major enhancement was to modify MATCH so that tracking is performed in three dimensions. This involves changes to the various internal database structures and to the processing of sensor reports. New routines were added to allow the processing of range-bearing-elevation type reports, range-bearing-elevation-range-rate type reports, range-bearing-altitude type reports and (x, y, z) positional reports. In addition, the processing of two-dimensional reports had to be modified in the case where the report was being considered as a two-dimensional observation of a three-dimensional track.

Another area of improvement involves modifications to the data rate false target model used within MATCH. Specifically, the data rate false target (DRFT) model has been segregated into several bins which can individually be associated with different sensors. In the past, there was only one DRFT bin. In particular, the data rate that was used was estimated from all sensors combined. Now data rates can be estimated separately for each sensor or group of selected sensors. One rational for doing this can be seen in the following example. Suppose that there are two targets A and B and two sensors C and D. Both targets are detected by both sensors, but target A is detected much more frequently by sensor C. All other things being equal, a contact report from sensor C is more likely to have been against target A than target B. Other reasons for this approach are to better accommodate characteristics of various sensors against different type of targets. Also, the numerical integration in the time cost function was made more accurate. This was required given the types of parameters we use to manage clutter.

A new feature added to MATCH is the dynamic target motion model. Now a track has an initial motion model that is used until a track is established. Once established the track either adopts a static permanent motion model or a model that adjusts the root mean square speed parameter to any of several choices. The initial model usually is adjusted to detect nonmaneuvering targets. This results in the correlation algorithm being less likely to string clutter together and initiate a track from clutter (e.g., radar noise). A true target traveling on a constant course and speed trajectory will initiate a track. After a few contacts, the motion model for a track is changed to accommodate maneuvering targets. We optionally allow a track's motion model to adjust its root mean square (rms) speed once the target track has demonstrated that we should be using a different speed. In this way, slow targets may not need to be tracked using a large root mean square speed just to accommodate the fact that other targets are going fast. This is another form of clutter management. Tracking with too high an rms speed parameter makes the algorithm more likely to associate clutter with a real track, if the actual target return is not received by the sensor.

Another enhancement to MATCH is a data throughput speed up package. This package maintains a rectangle of plausible positions for each track. When a report is processed a plausible rectangle (or wedge for bearings only reports) is created for the report. If a report's rectangle (or wedge) and a track's plausible rectangle do not overlap then the report will not associate with the track. This quick elimination test avoids further processing on tracks that have no chance of correlating with a given report. A track's plausible rectangle is saved and reused across many reports, until its recomputation is required.

Finally, Dr. Eric Butts of our Malvern office, together with Dr. Butler worked on the implementation of a double integrated IOU motion model. A preliminary prototype version of MATCH is being developed which will maintain two motion-model hypotheses for each "map" (a hypothesis of a given set of contacts representing a single target). This will enable MATCH to track highly maneuvering targets more accurately. This version of MATCH is still in the development stage.

3.2. MSI Through MATCH

During the time when the enhancements described in section 3.1 were being made to MATCH, we also began to address the issue of using MATCH as a stand-alone MSI algorithm. We created a version of MUSSLE in which all the sensor reports were fed into MATCH and MATCH performed the correlation and tracking function in its entirety. Preliminary results indicated that while MATCH was capable of handling all the data, the resulting track picture was not as correct as that of the MUSSLE algorithm. The main reason behind this is the extensive processing performed in MUSSLE to handle various sensor anomalies (e.g., IFF Azimuth Jitter, Radar multipath reports). Upon careful analysis we realized that extensive modifications would have to be made within MATCH to enable the processing to compare favorably with that of MUSSLE. Furthermore, there is a "chicken and egg" type problem with the remote data in that the data needs to be corrected for bias before being sent to MATCH, but the bias corrections factors (pads) can only be determined after the data has been sent to MATCH. Given these considerations, a decision was made to suspend investigation into this area of research and focus our efforts on the other tasks.

3.3. Enhancements to MUSSLE

The architecture of the MUSSLE algorithm was redesigned in order to increase the efficiency and hence the speed of the algorithm. The original software was built solely to demonstrate the ability to solve the Multiple Sensor Integration problem. While the basic algorithm did not change, a number of improvements were made to "optimize" the code. These

improvements included major revisions to the database structure maintained by MUSSLE, improvements in the data flow within the algorithm and optimization of the code in low-level terms such as use of in-line code segments and hard coded matrix operations.

Dr. Butler also worked on the problem of bearings-only (passive) tracking which occurs during receipt of ECM jamming strobes and during periods when the ESM sensor is receiving detections, but the radar is not active. All of the passive tracking techniques involve linearization of the observation in order to use the Kalman filter (which is a linear process) to update the state of the track. The key variant in passive tracking involves the choice of the linearization point. A new approach combining the use of the posterior mean and an iterative computation was implemented and appeared to give reasonable performance in preliminary testing.

In a parallel and related effort, the MUSSLE algorithm was used in the Best of Breed Tracker Competition. The preliminary evaluation (measures of evaluation results) conducted by the MITRE personnel, led to a number of minor improvements to the MUSSLE algorithm. These included changes to the processing of suspected IFF azimuth splits, improvements in the tracking performance during high speed maneuvers, and an enhancement in the processing of the linked list of correlation hypotheses which allows the algorithm to accept the correct hypothesis more readily.

Dr. Butler completely redesigned the method used for internally maintaining and propagating the track numbers that are used to tag the output provided to the FET. In the previous design, each raw track and each correlation (association of two or more raw tracks) in the database was assigned an internal track number. These track numbers were then converted to an external track number, if this track was being output to the FET. The logic used to maintain an internal consistency between track numbers for raw tracks and track numbers for correlations containing raw tracks was extremely complicated. The logic worked correctly when all tracks were automatically initiated everywhere (ATIZONEFLAG = TRUE), but there were some problems related to operator initiated and ATI Zone initiated tracks. Rather than attempt to modify the logic to correct the deficiencies, Dr. Butler redesigned the track number system completely and is in the process of testing and debugging the new code.

Finally, the code related to forming the initial correlation between two raw tracks was completely rewritten. In the previous design, the correlated track was initialized with the state and covariance of the "earlier" track and the reports from this scan only were used to update the state and to estimate the likelihood that the correlation is correct. This approach was modified so

that the correlated track is initialized with the state and covariance obtained by optimally combining the states and covariances of the raw tracks.

If the states and covariances of the individual raw tracks, at a common time, are given by (x_1, Σ_1) and (x_2, Σ_2) respectively, then the minimum variance estimate for the correlated track is given by

$$x = \Sigma_2(\Sigma_1 + \Sigma_2)^{-1} x_1 + \Sigma_1(\Sigma_1 + \Sigma_2)^{-1} x_2$$

and the covariance is given by

$$\Sigma = \Sigma_2(\Sigma_1 + \Sigma_2)^{-1} \Sigma_1 \quad .$$

3.4. Throughput and Memory Requirements Analysis

In accordance with task 4.1.8, Dr. Butler and Mr. Thompson produced a timing study of the MUSSLE program. Dr. Butler modified an existing Wagner Associates data generation program in order to simulate the various AWACS sensors. He also developed a scenario based on guidelines provided by ESC for the BBT competition. By running the program on the simulated data and extrapolating to a problem size of 3000 targets, we were able to arrive at the desired memory and throughput estimates. Additional details are contained in the report itself, which was delivered to Capt. Caccuitto on October 22, 1996.

3.5. Demonstration of the Data Fusion/Correlation Algorithm

On June 26, 1996 two missiles were launched from Vandenberg Air Force Base (AFB) asp part of the Minuteman III Follow-On Test an Evaluation (FOT & E) Program. The launches were tracked by radar at Vandenberg AFB (X-band) and Beale AFB (Pave Paws), both in California. The tracking data was relayed to the National Test Facility (NTF) in Colorado Springs, Colorado, where it was processed as part of the Target of Opportunity (TOO) Integration Checkout (TOOIC). In support of the TOOIC, conducted post-test fusion using the data as recorded in real-time and the Wagner Associates Data Fusion/Correlation Algorithm (DFCA). The fused data was compared to the Best Estimated Trajectories (BETs) as supplied by the Western Range. Additional details are contained in the TOOIC memorandum from Dr. David Kierstead, which was supplied as part of the monthly progress report for the month of September 1996.